VACUUM INTERRUPTERS – SEALED FOR LIFE

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ABSTRACT

In the medium voltage range the vacuum interruption principle is well established. Today vacuum circuit breakers are available in the medium voltage range up to 52 kV rated voltage and 80 kA short circuit current.

Field experiences reveal high reliability of the vacuum interrupter (VI) with mean time to failure (MTTF) of more than 40,000 VI-years. Due to high-tech production processes and modern VI designs with ceramic housings, above-named manufacturer's VI devices are maintenance-free.

At the beginning of VI mass-production 30 years ago there was a genuine concern about the vacuum integrity which might have been due to the glass insulation body in the manufacture of those early VI´s. In addition, vacuum test systems to assure vacuum tightness of the bottles were limited in pressure resolution to the range of 10^{-7} hPa. This caused an uncertainty in the predictions concerning vacuum tightness within a magnitude of 10^{-4} hPa after 30 years storage time for unused VI´s (an internal pressure of 10^{-4} hPa was determined as the functional limit). This did not imply the interrupter would loose vacuum during that time or reach the end of vacuum life. Precision of today's measuring apparatus has grown to an uncertainty of 10^{-4} hPa over more than 50 years. Measurements at any old VI may be older than 35 years and equipped with ceramic insulation body, verify those VI´s being really sealed for life. VI´s don't show increase of internal pressure due to leaks or gas permeation. Leaks caused due to the manufacturing process are greater than 10^{-6} hPa · l/s and will be certainly detected during the manufacturer's quality control.

VI´s also don't show long-term ageing effects. Experiences over more than 35 years of users and above-named manufacturers with vacuum interruption technology prove there is no limiting value within this period of time or even more.

INTRODUCTION

In the medium voltage range the vacuum switching principle is well established. Today vacuum circuit breakers are available up to 52 kV rated voltage and 80 kA short circuit current.

Main advantages are:

- High number of operations
- Maintenance-free operations
- Vacuum integrity by a sealed for life system
- Environmental compatibility

Most of the applications are in use at power transmission and distribution networks. However the vacuum interrupting principle is entering new domains which have been dominated by other quenching media in the past.

The different AC switching devices have in common the principle of arc interruption during current zero. Differences are founded in the extinguishing media. During middle of the 20th century air- and oil-circuit breakers dominated the medium voltage applications. Since the seventies SF_6- and vacuum interrupters (VI) have gained attention. Today more than 60% of switching devices applied in the medium voltage range from 3.3 kV up to 52 kV are VI´s. In the past, the vacuum switching technology was first developed by American (Jennings, General Electric, Westighouse) and British (English Electric and Vacuum Interrupters Ltd [now AREVA T&D].) manufacturers, followed by Japanese (Mitsubishi, Toshiba, Meidensha and Hitachi) and Germans (ABB and Siemens).

The main reasons for such a long development time of the VI´s have been shortcomings in industrial vacuum technology as well as a lack of fundamental knowledge about the vacuum arc behaviour. Finally, long term basic research and development made the introduction of a new modern switching principle possible. Convincing the customer to move from proved switching principles to VI´s was not easy at the beginning. It was enabled by providing information concerning the function principle, properties and reliability of VI´s especially by using a ceramic body as the insulation material instead of glass. Glass is vulnerable by permeation of both gasses Hydrogen and Helium. When the VI was first introduced into circuit breakers products the end users expressed two major concerns:

- What is the reliability of the VI in terms of service life?

- How reliable is the vacuum body over its design life and will the required vacuum remain over the shelf life?

At first the number of sold vacuum circuit breakers was limited, but since 1980 there has been a rapid increase in world wide demand. The global production (excluding China) in 2004 was approximately 1,2 million VI´s for medium voltage circuit breakers. Within Europe (including Russia) the estimated unit quantity is about 400,000 in 2004. E.g. ABB, Eaton Electrical, AREVA and Siemens together sold more than 800,000 units in 2005. In more than 35 years of experience a measure for reliability was obtained in the form of meantime to failure (MTTF) of 40,000 VI-years. This knowledge is an important base for further development of VI´s.

The manufacturing technology and design of VI´s changed in parallel with the increased output. At the beginning the VI´s were produced by a so called two-step brazing production technology. After pre-assembling and brazing of contact and lid parts the VI´s were mounted, welded and evacuated via an exhausting pipe. Today the one-shot brazing technology is well established **Fig. 1**. Through this the complete VI is being assembled in a dust-protected environment in a clean room. In batches of several tens or hundreds, the VI´s materials will then be degassed, evacuated and brazed simultaneously (one-shot) at 800 ... 900° C in an ultrahigh-vacuum furnace in one process step. This technology is an important premise for economical mass production of VI´s.

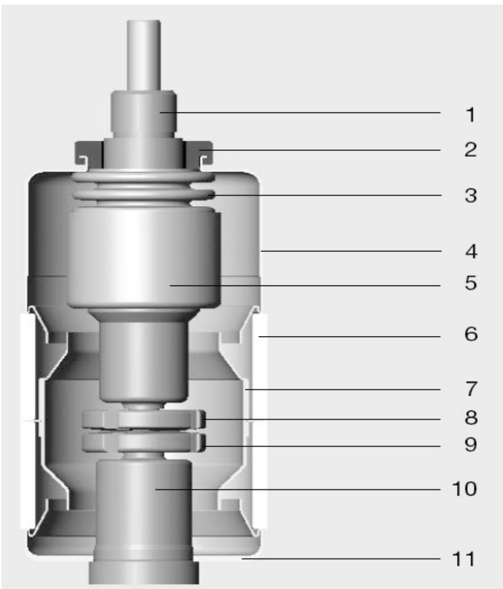

Figure 1. Section of a ABB VI schematic diagram (**1**: Movable stem; **2**: Twist protection; **3**: Metal bellows; **4**: Interrupter lid; **5**: Shield; **6**: Ceramic insulator; **7**: Shield; **8**: Moving contact; **9**: Fixed contact; **10**: Fixed stem; **11**: Interrupter lid)

To produce the vacuum in the range of 10^{-7} hPa or less turbo-molecular- or cryo- pump systems are the best choice. During heating up in the vacuum furnace the VI materials are extremely degassed and the water vapour desorbs from the inner surfaces completely. After cooling down the tightness of the VI´s has to be controlled. Normally, the PENNING-system (so called magnetron system) is used, in which the residual gas in the tube is 100% ionized by an impulse voltage in a magnetic field [1, 2, 3]. The ion current is a direct measurement for the internal pressure. Multiple measurements within a certain time provide precise information concerning the vacuum tightness [3].

At the beginning of industrial mass production several discussions concerning the VI shelf life came up. Theoretical considerations about the functional limit due to internal pressure $\mathbf{p_i}$ were based on the mean free path $\mathbf{\Lambda}$ of the molecules inside the VI.

In the case of air (mainly N_2) one obtains following relation:

$$\Lambda \cdot p_i \approx 6.3 \cdot 10^{-3}\, m \cdot Pa$$

If $\mathbf{p_i}$ exceeds the range of 10^{-4} hPa, the mean free path $\mathbf{\Lambda}$ is in the order of the interrupter length. Thus, 10^{-4} hPa was assumed to be the functional limit. With increasing experiences however, basic investigations indicated the limit pressure being orders of magnitudes higher. Nevertheless the limiting value of 10^{-4} hPa is established in the literature.

The first PENNING systems had a measuring resolution in the range of $\Delta p_{res} \approx 10^{-7}$ hPa. This results in an uncertainty of 10^{-7} hPa/10 days, if the multiple measurements are done in between an economically justifiable storing time of 10 days before delivering. From this point of view an uncertainty of $\Delta p \approx 10^{-4}$ hPa will be reached after 30 years [4]. Thus, the early manufactures of VI´s acted on the assumption of 30 years operating time for the devices [5].

Today millions of VI´s are in service since more than 30 years without "loss of vacuum". The reliability is proven by field experience and expressed by an MTTF better than 40,000 interrupter years **Fig. 2**.

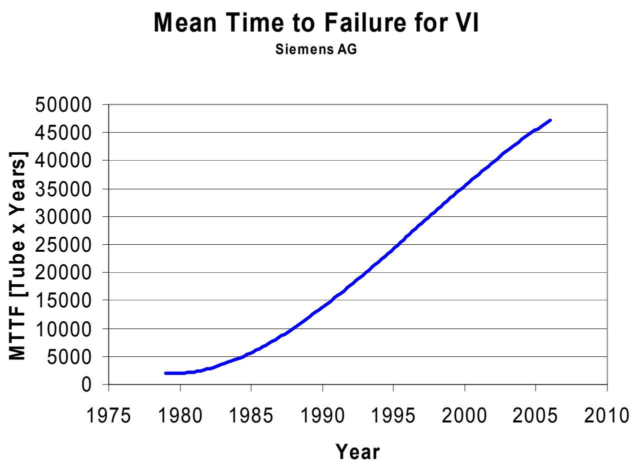

Figure 2. Mean **T**ime **T**o **F**ailure (**MTTF**) is a statistical value and meant to be the mean over a long period of time and large number of units

The intention of this paper is to inform all whom it may concern about the present state of the art and to define the statement for modern VI´s which is: "***SEALED FOR LIFE***".

LEAKS AND INTERNAL PRESSURE

Typical values of the internal pressure are in the range of 10^{-7} hPa or even lower. Preconditions to reach and permanently maintain this level are, together with the above mentioned manufacturing technologies, high sophisticated interrupter designs and carefully selected materials of high purity, especially Al_2O_3 for ceramic insulation being properly metallised, oxygen-free copper (OF-Cu), extremely degassed contact materials and adequate high-temperature brazing materials.

In very few cases leaks may occur due to unpredictable events, like failure during the production process, mechanical destruction, corrosion or external electrical flashover. These leaks will ventilate the interrupter chamber immediately. To qualify the leaks, it has to be considered the leakage rate:

$$\dot{Q}_L = \frac{\Delta p_i}{\Delta t} \cdot Vol \qquad (1)$$

with the increasing of internal pressure Δp_i per time unit Δt in the interrupter volume Vol. On the other hand the leakage rate depends on the geometry of the leak, described by the conductance L and the difference between the external pressure p_{ext} and the internal pressure p_i:

$$L = \frac{\dot{Q}_L}{p_{ext} - p_i} \qquad (2)$$

In the unlikely event of a leakage the rate will be determined with a commercial helium leak detector system and the leak geometry has to be analysed by micro cross section views. Derived from the long term experience one can classify the leakages $\dot{Q}_L$ into the following types:

- **Failures during manufacturing**
  $\dot{Q}_L \geq 10^{-2}$ hPa · l/s
- **Mechanical damages** (bellows, flanges)
  $\dot{Q}_L \geq 10^{-4}$ hPa · l/s
- **Corrosion** (at the initial stage)
  $\dot{Q}_L \geq 5 \cdot 10^{-5}$ hPa · l/s
- **Flashover outside** and through the ceramic
  $\dot{Q}_L \geq 10^{-3}$ hPa · l/s

Real leaks are $\geq 5 \cdot 10^{-5}$ hPa · l/s (worst case) and would ventilate the interrupter chamber in less than one year. However, typical values due to an unexpected event in the field – such as an external flashover or mechanical damage – are in the order of $\geq 10^{-3}$ hPa · l/s, causing a loss of the vacuum in less than one day.

From these facts can be clearly derived that early failures in between 5 years after manufacturing only are observed in very rare events. Long term effects, like the mechanical life of the bellows, are well determined.

Another influence on the internal pressure of vacuum interrupter (VI) can be so called virtual leaks. They are caused by hidden gas filled volumes inside the interrupter, such as pores or design failures. In the modern interrupters virtual leaks have no relevance anymore.

Like any surface contamination also fingerprints have an effect on the vacuum quality. One released mono-molecular layer from the inner surface would produce a pressure increase of about 10^{-6} hPa. This will be avoided by intensive surface treatment and clean room assembly. There is also a "natural" surface wetting of the interrupter parts with water vapour from the atmosphere during manufacturing. However the one-shot brazing process at 800 … 900° C removes the water vapour completely from the surfaces.

Finally one has to consider the influence on the vacuum integrity due to gas permeation from the outside. The only possibility for this effect is H_2 permeation through the stainless steel bellows because of it's very small molecule diameter. The upper limit of the internal pressure is given by the partial pressure of hydrogen in the atmosphere, which is in the range of 10^{-4} hPa. Hence, the internal pressure in the VI will not exceed 10^{-4} hPa due to gas permeation from outside.

VACUUM INTERRUPTER SHELF LIFE

A vacuum interrupter (VI) can and should be continued to be used for as long as it passes a high AC or DC withstand voltage test, proving that it still shows an acceptable vacuum. There are existing VI´s manufactured 35 years ago known as still operating reliable.

The VI has gone through the final assembly, evacuation, degassing and brazing process. The completed VI has to have a vacuum pressure down to 10^{-7} hPa or even lower. The usual method of measuring the vacuum pressure is the magnetron method [1, 2, 3] which has been found to be extremely reliable and easy to incorporate into the production process.

To clarify the situation at the upper vacuum pressure level in the range of 10^{-3} hPa a purposely manufactured sample was established and tested:

- It's short circuit current interruption ability and high dielectric withstand voltage performance are equal and similar to one having a final pressure of 10^{-5} hPa or even lower
- If the vacuum pressure inside the VI is e.g. two orders of magnitude lower than the Paschen curves minimum value (1 hPa · cm), the VI will perform perfectly.

The VI must be designed and manufactured to have zero leakage rate. There have been some publications [6] discussing a leakage rate to maintain a 30 year sufficient vacuum pressure of up to 10^{-2} hPa. However these reports do not take into consideration the unique nature of vacuum seals and vacuum tightness in an environment such as atmospheric air. What really matters is to determine the quantity of leakage that can be tolerated. No one really knows the true period of time commercial VI´s can retain vacuum below the limitation level of up to 10^{-3} hPa [7]. From our experience a 30 years life expectation certainly imposes very strict requirements to the body design, the material and the brazing of all joints that are exposed to the ambient atmosphere [8]. If we conservatively assume a maximum allowable vacuum pressure at the upper limitation value of up to 10^{-3} hPa the maximum amount of gas allowed to leak $\dot{Q}_L$ into a VI is determined in accordance to equation 1.

The amount of gas that can leak into the VI depends on the leakage type and dimension. Table I illustrates the maximum allowable hypothetical leakage rate for VI´s with an assumed volume of one liter to reach the limitation level of up to 10^{-3} hPa as a function of time.

Table I: Leak rate for VI, achievable lifetime, Vol. 1 liter

Type of leakage	$\dot{Q}_L$ leakage rate [hPa · l / s]	Lifetime	Remarks*)
Macro size	$> 10^{-2}$	Lower than some minutes	Detectable
Micro size	$\dots 10^{-5}$	6.5 hour	Detectable
Submicro size	$\dots 10^{-7}$	27 days	Detectable, increase of pressure at second measurement

*) First three leakage types are detectable at the manufacturing plant, first and second magnetron pressure measurement [9].

It results that leakages rates smaller than 10^{-12} hPa · l/s are very unlike and not observed, thus they are of no practical importance for the shelf life. A leak check level to that sensitivity is enough to guarantee its vacuum integrity over required shelf life. From the Table I it can safely be derived there will not be a leakage larger smaller than 10^{-10} hPa and unlikely to continuously leak for its entire application (service) time [7]. Under severe environmental atmosphere conditions corrosion effects may occur during less than 5 years after manufacturing. To test the VI in service the contacts should be opened to the nominal contact gap to confirm the power frequency withstand voltage (e.g. 50kV (rms) at 10mm contact stroke).

DISCUSSION

During the last years we came aware of some utility customers replacing partly good vacuum interrupters (VI) in their switchgear simply because it has been 20 … 25 years since the panel boards were installed. Our experience of watching our VI´s used in the field all over the world, in vastly different environments, has been lasted for well over more than 30 years. It turned out that with proper vacuum and inert gas quarantine between two magnetron measurements carried out during the manufacturing process, VI´s are "sealed for life".

The only reason to limit the "shelf life" of a VI up to 30 years is based on the fact of an environmental impact from the atmosphere. Derived from our experience much longer than 30 years there is no risk visible to operate with a VI for that period under predefined conditions.

CONCLUSION

The production methods and the material used are well coordinated and strong precondition for long service life especially. Due to selection of materials like copper, ceramic, optimized steel and brazing materials (silver-copper), e.g. an excellence corrosion resistance is ensured by the manufacturing process.

Optimal preconditions for service life are ensured by considering the vacuum interrupter VI instruction manual. Long term factors - like mechanical life of the bellows - are well determined. Failures can be related to unexpected events like mechanical damage or external flashover. Up to now millions of VI´s are in service application use worldwide. This outstanding experience does best underline the success in VI shelf life over more than 30 years.

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